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HIGH-VELOCITY Lyα EMISSION FROM SNR 1987A

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ABSTRACT

The high-velocity Lyα emission from SN 1987A observed with the Space Telescope Imaging Spectrograph (STIS) evidently comes from a reverse shock formed where the outer envelope of SN 1987A strikes ionized gas inside the inner circumstellar ring. The observations can be explained by a simple kinematic model, in which the Lyα emission comes from hydrogen atoms with radial velocity ~15,000 km s^{-1} crossing a reverse shock in the shape of a slightly prolate ellipsoid with equatorial radius 4.8×10^{17} cm or ~80% of the distance to the inner surface of the inner ring. N V $\lambda\lambda$1239, 1243 emission, if present, has a net luminosity $\lesssim$30% times that of the Lyα emission. Future STIS observations should enable us to predict the time of impact with the inner ring and to determine unambiguously whether or not N V emission is present. These observations will offer a unique opportunity to probe the structure of SN 1987A's circumstellar environment and the hydrodynamics and kinetics of very fast shocks.

Subject heading: circumstellar matter — hydrodynamics — supernovae: individual (SN 1987A) — ultraviolet: ISM

1. INTRODUCTION

In the preceding Letter of this special issue of the Astrophysical Journal, Sonneborn et al. (1998) describe observations of optical and ultraviolet (UV) line emission from SN 1987A and its circumstellar ring taken with the Space Telescope Imaging Spectrograph (STIS). The UV spectrum (Sonneborn et al. 1998, Fig. 2) shows evidence of broad emission near Lyα, which may also include a contribution from N V $\lambda\lambda$1239, 1243. Borkowski, Blondin, & McCray (1997, hereafter BBMc) predicted that such broad emission lines would be observed from the shock interaction responsible for the X-ray emission seen by *ROSAT*.

Here (§ 2) we interpret the STIS observations of Lyα with a simple kinematic model. In § 3, we briefly discuss the N V emission that is expected from such a model. Then, in § 4, we describe how future STIS observations may be used to study the physics of the shocks responsible for the emission.

2. HIGH-VELOCITY Lyα EMISSION

Following Chevalier & Dwarkadas (1995), we assume that the X-rays seen by *ROSAT* come from shocked gas produced by the impact of the outer envelope of the supernova with a thick H II region (density $n_{\rm II} \sim 100$ cm^{-3}) that lines the interior of a bipolar nebula. The shocked gas is bounded on the outside by a blast wave that is moving into the H II region and on the inside by a reverse shock that is moving into the debris. The shapes of these shock fronts will be determined by the density distribution of gas in the H II region and in the outer supernova envelope, neither of which is well known.

BBMc fitted the *ROSAT* observations with a model in which a spherical supernova envelope [with a power-law density profile $\rho(r, t) \sim t^{-3}(r/t)^{-9}$] encountered an H II region that had the shape of a thick circular torus and uniform density. For such a model, most of the X-ray and ultraviolet line emission comes from a broad, ring-shaped region. But, as we shall show, the STIS observations lead us to a model in which the UV line emission is not confined to a zone near the equator.

Broad Lyα emission should come from the H I atoms in the outer supernova envelope that cross the reverse shock and are excited by impacts with electrons and ions in the shocked plasma. The cross sections for electron and ion impact excitation and ionization are much greater than the cross sections to deflect hydrogen atoms. Therefore, we expect that the Lyα will come from hydrogen atoms having a velocity distribution corresponding to a cold beam with radial velocity $V_r = r/t$, where r denotes the radius of the atom from the supernova center and t is the time since explosion.

We do not expect any Lyα emission associated with the forward shock because the hydrogen ahead of the forward shock was ionized by the supernova flash and would not have recombined appreciably since then.

For H I relative velocities of ~11,000 km s^{-1} and a shocked proton temperature of ~10^9 K, the charge transfer rate is ~10^{-2} times the impact ionization rate (Janev & Smith 1993), so the components of Lyα emission with velocity distribution representative of the shocked protons should have negligible intensity, unlike the case with shocks of lower velocity (Chevalier, Kirshner, & Raymond 1980).

The image seen through the STIS is a convolution of the actual brightness distribution of the emitting region in the STIS aperture with the dispersion of the spectrograph. If we assume, as argued above, that the Lyα emission comes from radially streaming hydrogen atoms, the Doppler shift of the emitting gas is not a free parameter but is given by the projection of the radial velocity at the reverse shock front.

It follows that if the spectrometer response were uniform, and the emitting region had cylindrical symmetry about the polar axis of the inner ring, the STIS image would have S-type symmetry upon reflection horizontally and vertically through the supernova center. But the actual STIS image will not be symmetric for three reasons. First, the light-travel time

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from the far (redshifted) side of the emitting region may be significantly (~1 yr) greater than that from the near (blue-shifted) side. Since we expect the Lyα emissivity to be increasing with time (by about 25% per year, according to BBMc), this light-travel time delay would cause the image on the blue side of the aperture to be somewhat brighter than that on the red side. Second, the throughput of the STIS optics and detector decreases rapidly to the blue of Lyα. For an extended source, photons that fall on a given location on the STIS detector do not necessarily have the same wavelength. Therefore, any removal of the spectrograph response function will not return the actual intensity distribution. This effect alone would slightly suppress the blue wing of Lyα. Third, since the local Lyα emissivity is proportional to the mass flux crossing the shock, which in turn depends on the steep density profile of the ejecta, an asymmetry in the shock front geometry will cause regions of the shock front to differ in brightness.

To construct a model STIS image, we assume a three-dimensional distribution of Lyα emission and a model for the increase of brightness with time. The Doppler shift of a given emitting region follows from the assumption of free expansion as noted above. Given the wavelength, we multiply the emission by the spectrometer throughput and interstellar extinction and place the resulting contribution to intensity at the appropriate position (and with the appropriate point-spread function) corresponding to the G140L grating dispersion (24 Å arcsec^{-1}, i.e., 6000 km s^{-1} arcsec^{-1} at Lyα). We then removed the spectrograph response by applying a wavelength scale that placed Lyα on ring center.

Figure 1*a* (Plate L36) shows the image that would result from a model similar to that proposed by BBMc. Here we have assumed that the Lyα emission comes from a ring-shaped equatorial section of a spherical surface of radius $r_1 = 4.8 \times 10^{17}$ cm (~80% of the radius to the inner boundary of the inner circumstellar ring). This choice ensures that the model STIS image will have a vertical dimension equal to the observed one. The ring is assumed to extend from $-30°$ to $+30°$ in latitude and to have constant Lyα emissivity per unit surface area. The left panel of Figure 1*a* illustrates how the emitting surface would appear in projection through the $2'' \times 2''$ aperture of the STIS if there were no dispersion. The ring center is displaced approximately 0."17 downward and 0."11 to the right of the center of the aperture. The major axis is tilted clockwise by 116° with respect to the dispersion axis, such that the near (N) side is to the right of center and the far side is to the left.

The right panel of Figure 1*a* shows the STIS image that would follow from such a model. The radial velocity of H I atoms crossing the surface is $V_1 = r_1/t \approx 15{,}000$ km s^{-1}, and the projected velocity of such atoms at the equator of this surface is $V_1 \cos 45° \approx 10{,}600$ km s^{-1}. As a result, the north (south) side of the ring image is shifted to the left (right) by $\approx 2''$ as a result of the dispersion of the STIS.

We were encouraged by the morphological similarity of this image to the actual STIS image, but after more careful inspection, we found that the observations mandate a model somewhat different than the one proposed by BBMc. The right-hand (redshifted) boundary of the model image extends 1."5 to the right of the aperture boundary, while that of the actual image extends 2."5 to the right. (The image on the blue side of the aperture is lost owing to the decreasing spectrometer throughput.) We cannot explain the STIS observations with any model in which the Lyα emission is confined to an equatorial band, because the maximum Doppler velocity is constrained by the requirement that the emitting surface must lie inside the inner ring.

However, we can produce a model STIS image that agrees much better (but not exactly) with the actual image if we allow the emitting surface to extend to the polar axis of the ring plane. Figure 1*b* illustrates a model in which the reverse shock is a prolate ellipsoid, with equatorial radius $r_1 = 4.8 \times 10^{17}$ cm, as in Figure 1*a*, and polar radius $r_2 = 5.8 \times 10^{17}$ cm. In this model, we have assumed that the supernova ejecta have spherical symmetry, so that the brightness of the emitting surface decreases with distance from the supernova center as r^{-8} owing to the assumed r^{-9} density law of the ejecta. The left panel shows the projected image of the emitting surface without dispersion, where again N marks the northern side of the surface. The right panel shows the model STIS image. One can see that the boundary of the image to the right of the aperture conforms fairly well to that of the observed image. The plus sign in the left panel indicates that part of the surface (on the far side of the ellipsoid) that maps to the rightmost boundary of the dispersed image (it does not necessarily have the largest redshift).

The model illustrated by Figure 1*b* does not extend as far to the right of the aperture as the actual STIS image, particularly toward the east of the remnant. This fact suggests that some of the supernova ejecta may extend farther in the polar direction than assumed in this model. We would not be surprised if the actual shock had significant departures from axial symmetry, as is clearly the case in the radio images that are brightest in the east (Gaensler et al. 1997).

Although the boundary of the model STIS image agrees fairly well with that of the actual image, the intensity distribution does not. The model image is brightened at its rim, while the actual image has a nearly uniform brightness profile. We cannot account for such uniform brightness with any model in which the Lyα emission is confined to a smooth surface. We can, however, reproduce the observed brightness distribution with a model in which the line emissivity is distributed in radius. For example, a model in which the Lyα emissivity varies as power law proportional to $(r/R_S)^2$, where r is the radius vector and R_S is the radius of the surface shown in Figure 1*b*, produces a fairly uniform brightness distribution.

This result suggests that there may be some mechanism at work to excite Lyα emission of H I atoms in the ejecta before they reach the reverse shock. We have checked one obvious candidate—excitation associated with ionizing radiation from the shocked gas—and found that it cannot account for the observed flux. Another possible source of excitation of H I in the unshocked ejecta is fast particles accelerated by the shock. Unfortunately, we do not know enough about the efficiency of such acceleration to say with confidence whether this mechanism is a likely explanation. Finally, we should not rule out the possibility that the reverse shock surface is not smooth at all.

The Lyα flux inferred from the STIS image is $F(\mathrm{Ly}\alpha) = (1.9 \pm 0.5) \times 10^{-13}$ ergs cm^{-2} s^{-1} (Sonneborn et al. 1998). This value includes the Lyα signal within the aperture, which is detectable above the geocoronal emission. It is close to the value $F(\mathrm{Ly}\alpha) = 2 \times 10^{-13}$ ergs cm^{-2} s^{-1} predicted by BBMc. By comparing the rates of impact excitation to the ionization of hydrogen by fast particles and tracing the radiative decay paths for the excitations, we calculate that for each H I atom entering the shock, approximately 1 Lyα and 0.2 Hα photons escape the remnant. The Lyα flux then implies that the rate of

H I crossing the reverse shock is $\dot{N}_H = (2.0 \pm 0.7) \times 10^{46}$ s^{-1}, where we have assumed a distance to the remnant of 50 kpc and an extinction factor 0.17 ± 0.03 for Lyα (Sonneborn et al. 1998). This value is reasonably close to the value $\dot{N}_H \approx 1.1 \times 10^{46}$ s^{-1} that we calculate for the flux of H I atoms in the outer envelope of Woosley's (1988) model 10H, which would cross the ellipsoidal surface of the model illustrated in Figure 1*b*.

We can also estimate the expected flux of broad Hα from the observed Lyα flux and photon ratio stated above. Allowing for differential extinction, we estimate $F(\mathrm{H}\alpha) = (2.8 \pm 1.0) \times 10^{-14}$ ergs cm^{-2} s^{-1}. This should be observable, both from the ground and with STIS.

3. N V EMISSION

BBMc predicted that the STIS should also see broad N V emission from SN 1987A. This emission is not clearly present in the STIS image; we can only say with confidence that the net flux of N V $\lambda\lambda$1239, 1243 can be no greater than 30% of Lyα.

The N V line profile is likely to be very different from the Lyα profile. First, as BBMc have shown, the fraction of nitrogen in the H II region ahead of the blast wave that is in ionization stage N V or lower is uncertain but probably $\gtrsim 0.08$. In their model, the mass flux through the blast wave is greater than that through the reverse shock (by a factor 2); therefore, a significant fraction of the N V emission may come from N V ions that enter the shocked region through the blast wave. On the other hand, almost all the nitrogen atoms in the supernova envelope are in ionization stage N V or lower, and so will give rise to N V $\lambda\lambda$1239, 1243 emission upon crossing the reverse shock.

The velocity distribution function of the N V ions is likely to be very different from that of the excited H I atoms. Although the Coulomb collision cross sections of N V ions are substantially less than excitation and ionization cross sections, the ions can be deflected easily by magnetic fields. (A magnetic field $\sim 10^{-9}$ of the equipartition field would be sufficient to deflect the ions in a path length less than the ionization path length.) If deflection by magnetic fields were the only acceleration mechanism, the velocity distribution function of the shocked N V ions would be a spherical shell with a centroid at the fluid velocity, V_s, of the shocked gas and a radius $\Delta V = V_t - V_s$, the difference between the streaming velocity of the unshocked nitrogen ions and the velocity of the shocked fluid. The local emissivity resulting from such a velocity distribution function would have a rectangular line profile with a centroid at V_s and a full width $2(V_t - V_s)$.

But such a distribution function may also be unstable, and the shocked N V ions may be accelerated by turbulent plasma waves associated with collisionless shocks (e.g., Stone & Tsurutani 1985; Cargill 1991). However, we are unaware of any collective process that is likely to result in the equipartition of thermal energy between nitrogen ions and protons on timescales much less than the timescale for energy exchange by Coulomb collisions. Therefore, we assume here that the shocked N V ions will have a Maxwellian distribution function with velocity dispersion ΔV^2. This assumption is consistent with the discovery of broad UV lines by the Hopkins Ultraviolet Telescope in a nonradiative shock in the remnant of SN 1006 (Raymond, Blair, & Long 1995). If so, the local N V $\lambda\lambda$1239, 1243 emissivity resulting from N V ions that cross the reverse shock will have a Gaussian profile with a centroid at the projected velocity of the shocked fluid and a (one-dimensional) dispersion $\Delta V_R \approx 9000$ km s^{-1}, where we have estimated $V_s \approx 4000$ km s^{-1} from the hydrodynamic model of BBMc. Likewise, the local emissivity from N V ions that cross the blast wave will have a Gaussian profile with the same centroid and dispersion $\Delta V_B \approx 3300$ km s^{-1}.

Figure 1*c* illustrates the STIS image that would result from N V $\lambda\lambda$1239, 1243 emission. For this model, we have assumed that the luminosity of N V from ions that cross the blast wave is equal to 20% of that from the ions that cross the reverse shock. Note that the centroid of N V $\lambda\lambda$1239, 1243 is shifted by 1″ to the right of Lyα in the STIS observation. The shape of the N V image is much different from that of Lyα because the N V emissivity at any given point in the shocked gas has a very broad line width, in contrast to the Lyα emissivity, which is nearly monochromatic.

Since the observed STIS image does not resemble the model N V image shown in Figure 1*c*, we conclude that the observed image is dominated by Lyα. We constructed composite simulations in which we added various fluxes of N V $\lambda\lambda$1239, 1243 having the image shape of Figure 1*c* to the simulated Lyα image of Figure 1*b*. Our estimate that the flux of N V $\lambda\lambda$1239, 1243 can be no greater than 30% of the Lyα flux is based on eyeball comparisons of such simulations with the STIS observations. This upper limit is roughly equal to the N V flux predicted by BBMc.

4. THE FUTURE

The observations of broad Lyα demonstrate the enormous power of STIS to measure the hydrodynamics and kinetics of the impact of SN 1987A with its circumstellar environment. The present observations suggest that the double shock structure is closer to the inner circumstellar ring than predicted by BBMc, that the Lyα emission is not confined to an equatorial band, and that the emissivity may be distributed in radius. With STIS observations spanning 2 or 3 yr, we can measure the time dependence of the Lyα flux, profile, and proper motion.

The current observations indicate that the reverse shock surface has an equatorial radius ~80% of the inner boundary of the inner ring. Although the position of the blast wave is not known precisely, it must be quite close to the inner ring. It appears that the blast wave will strike the ring earlier than the date A.D. 2007 estimated by BBMc. Indeed, this impact may already have begun at the "hot spot" on the ring observed by Garnevich, Kirshner, & Challis (1997). The ~250 km s^{-1} blueshift of Hα seen at this spot by Sonneborn et al. (1998) is consistent with the notion that the blast wave has just entered an inward protrusion of the dense ring at this location. If so, we would expect this spot to continue to brighten, and more such spots to appear in the next few years.

While we have seen that the STIS is uniquely suited to measure the kinetics and dynamics of this extraordinary event, we recognize that the present observations are not optimal for this purpose. With such a large aperture, the spatial and spectral information cannot be isolated from each other. Figures 1*d* and 1*e* illustrate what we might see with the 0″.5 slit centered on the supernova and oriented at P.A. = 203°. For this simulation, we have assumed the same prolate shell model for the emitting surface as in Figure 1*b*. One can see that it is possible with such an observation to measure accurately the position of the emitting surface and the expansion velocity. If the Lyα emissivity is not confined to a thin shell, we will be able to measure its radial distribution. Moreover, if the N v $\lambda\lambda$1239, 1243 signal is strong enough, one can clearly distinguish its profile (Fig. 1*e*) from the Lyα profile (Fig. 1*d*). This observation will provide an unprecedented opportunity to probe the kinetics of collisionless shocks.

The observation illustrated by Figures 1*d* and 1*e* is already scheduled, and the data may be available soon after this Letter is published. But they will not tell the whole story. Clearly, it is imperative that we map the entire emitting region and follow its rapid evolution with STIS, as we prepare for the main event (Luo, McCray, & Slavin 1994).

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